Chapter 6
Transportation

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Abstract Transportation of lignocellulosic biomass feedstock is an important task within a biomass-based energy provision system. The distributed availability of low-density feedstock makes this operation highly challenging. The proposed aim to replace a large percentage of fossil fuels with renewable lignocellulosic bioenergy sources by the year 2030 [1, 2] will require adaptation and possibly renovation of the existing transportation infrastructure. The complexity of the biomass provision system will be further increased as compared to the current system since the biomass feedstock portfolio will consist of a range of energy crops, grown in various locations with unique climates and transportation infrastructures.

Ideally, biomass would be preprocessed into a gravity-flowable particulate bulk form that allows utilization of and expanding upon the existing transportation infrastructure of agricultural bulk products such as corn and soybean. Such a form would require size reduction of feedstock, which is energetically expensive, followed by compression. To optimize long-distance transport, the bulk density of this feedstock would ideally be as high as that of coal in railcars. This would require very high "in-mold" particulate densities of the feedstock generated by machines with very high throughput. Even if this goal could be achieved, it is currently not clear what the effect of such a highly densified material form on the conversion efficiency would be.

Finally, apart from technical challenges in producing the ideal form of biomass from a provision and conversion perspective, there is a huge challenge in the mere scale of the proposition: If the goal set by the US government of replacing 30 % of

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current fossil fuels by 2030 is to be reached, the annual transported volume of biomass would be three times that of the 2011 US corn yield.

This chapter reviews the literature on research that addresses biomass feedstock provision including transportation and identifies challenges that must be addressed in the near future.

6.1 Introduction

The US Biomass R&D Technical Advisory Committee has recommended a 30 % replacement of the current US oil consumption with biofuels by 2030 [1, 3]. This is motivated by the desire to move towards sustainable sources of energy to address looming problems such as climate change and energy security. The sources of biomass feedstock are highly distributed because high biomass yielding energy crops are limited to specific growth regions characterized by land use policy, water availability, soil type, climate, and latitude.

In first-generation biofuels, corn starch and sugar cane are converted into ethanol, while vegetable oil, soybean oil, palm oil, and similar sources are converted into biodiesel. Since these sources are conventional agricultural products, the transportation of first-generation biofuel feedstock can employ the infrastructure built for corn, soybean, and other field crops. A drawback of first-generation biofuels is that the crops used as feedstock compete with food production. In contrast, second-generation (advanced) biofuels are produced from lignocellulosic nonfood sources, such as agricultural residues, energy grasses, forest residues, and woody plants. With the emergence of second-generation biofuels, new challenges have arisen, since crops such as Miscanthus, switchgrass, and energy cane need to be efficiently harvested, preprocessed, stored, and transported. Since these are not conventional agricultural products, the existing infrastructure is not optimized for their transport. Firstly, size reduction (comminution) is required, because no conversion process can process uncut material directly. Secondly, the energy density of the crop in the field is very low, and compression beyond baling is needed for long-distance transportation [4]. Thirdly, the scale of feedstock provision is huge: The goal of a 30 % replacement of the current US oil consumption by 2030 will increase the annual demand for feedstock to one billion dry tons of cellulosic feedstock, which is more than threefold the 2011 US corn production [1, 2, 5]. Biomass can be combusted directly (either for domestic heating or commercial power generation) or in combination with fossil fuels such as coal, but even here challenges arise, mainly because of the biomass' high ash content. The logistics of direct combustion are relatively straightforward. For domestic heating, the biomass is preprocessed into pellets, briquettes, woody chips, or bundled firewood logs, which are also produced from prairie grass feedstock, sugar cane bagasse (a by-product of sugar cane ethanol production), or agricultural residues (e.g., corn stover). For commercial power generation, biomass can be co-combusted through blending with coal, converted into a gas, or fed directly into a furnace.

The production of liquid fuels is achieved through thermochemical/hydrothermal, biochemical, and/or chemical processes, with or without pretreatment. These processes typically produce ethanol or bio-oil as the fuel. The liquid biofuel production chain consists of three sequential parts: (1) feedstock provision, (2) pretreatment, and (3) conversion. If the complete liquid biofuel production chain is to be optimized, the biomass material must be preprocessed into a form that optimizes each of the three parts, but unfortunately they are not necessarily in agreement: The optimal form of the material during the feedstock provision phase is dominated by handling and transportation requirements. For instance, to optimize the provision phase, the material should ideally be preprocessed into a form that minimizes losses (e.g., by limiting dust), flows under gravity to allow the use of traditional conveying equipment such as augers, chutes, and conveyor belts, and have a sufficiently high bulk density to ensure that the transportation equipment reaches its weight and volume limits simultaneously. From this viewpoint, stable biomass consisting of flowable particulates of consistent size and shape with a high material density would be ideal. This concept has been captured in the Uniform Format as defined by Idaho National Laboratory [6]. The aim here is to gradually transition from “Conventional Bale” systems through a “Pioneer Uniform” system, which uses mainly existing equipment, to the futuristic “Advanced Uniform” system, which provides stable solid biomass in a blendable, tradable commodity form. The target is to reduce the cost of delivered biomass from US\$100 ton^{-1} in 2007 to US\$30 ton^{-1}, in 2017 [6].

To optimize the complete biofuel production chain, the provision phase must produce materials in a form that are well suited for pretreatment, which must transform them into a form that allows for optimization of conversion. Pretreatment is a process in which the structure of the lignin, cellulose, and hemicellulose matrix is broken down to enable enzymatic activity during hydrolysis. This can be achieved by chemical methods using acids and ionic liquids, using enzymes, using physical methods (such as the classical steam explosion process used in corn ethanol production), or by using a combination of chemical and physical methods, such as the ammonia fiber explosion (AFEX) method [7, 8]. The extent to which the pretreatment method is robust with respect to the biomass form is not known for most bioenergy crops. Although AFEX employs a physical explosion process, it is sensitive to particle size in the case of corn stover [9]. In general, for pretreatment methods that do not incorporate physical separation processes, the ideal particle size may be as small as 80 µm. This is achievable by ball milling the material for a rather long time. However, research on *Miscanthus giganteus* has shown that size reduction to such a small size requires 100 % of the inherent heating value (PIHV) of the material. Therefore, the optimal particle form for conversion is to a large extent determined by the trade-off between the energy requirement for comminution and the increased conversion efficiency for smaller particle sizes. As a general rule, the feedstock must be comminuted into particle sizes ranging from 9.35 to 25.4 mm with pretreatment and smaller than 1 mm without pretreatment. Table 6.1 shows an overview of typical particles sizes as a function of conversion technologies and feedstock.

The chapter is arranged as follows: Firstly, various types of feedstock currently either employed or under investigation are addressed. Secondly, preprocessing

Table 6.1 Biomass feedstock type and forms matrix for four categories of conversion technology[a]

Biomass conversion technology	Major outputs and products	Preferred feedstock types	Feedstock form requirements
Gasification	Electricity, thermal energy, hydrogen, bio-oils, charcoal	Dry feedstock	Coal size particle distribution
Pyrolysis	Bio-oil, charcoal, electricity, thermal energy	Any feedstock (<10 % moisture content preferred to assure high heat transfer rate)	<6-mm particle (1–2 mm preferred)
Biochemical ethanol production	Ethanol, lignin, electricity, and heat	Cellulosic/woody biomass	<9.35- to 25.4-mm particle with pretreatment, <1 mm without pretreatment
Chemical biodiesel production	Biodiesel, soaps, and glycerin	Bio-oil from feedstock gasification or pyrolysis	The same as gasification and pyrolysis

[a]Adapted from [48] and [11]

operations are discussed with an emphasis on energy requirement. Thirdly, transportation of biomass using truck, rail, water, and pipeline are addressed. Fourthly, a section is devoted to future directions, which discusses challenges and potential areas of research. A summary concludes the chapter.

6.2 Types of Feedstock

In a first-generation feedstock such as corn for ethanol production, the form of the material is essentially unchanged from harvest until milling takes place in the biorefinery. The reason is that corn kernels in bulk form comprise a near-ideal granular material that is gravity flowable with a relatively high bulk density of 720 kg m^{-3}. In addition, an expansive transportation system that includes elevators with drying facilities, roads, railroads, and waterways has been built over the past century. Sugar cane is mostly harvested in billet form and directly delivered to the sugar mills or the biorefinery using truck transport without intermediate storage because of the perishable nature of sucrose. In the processing plant, the material is separated into juice with a high sugar concentration and a cellulosic bagasse sidestream.

The logistics associated with second-generation biomass feedstock are more challenging than those of first-generation feedstock. As an example, harvesting of the high-yielding energy grass *Miscanthus giganteus* takes place in winter, at which time the crop consists of bundles of tall thin stems that can be cut and baled using adapted hay baling equipment (Fig. 6.1). Second-generation biomass bales typically have a density ranging from 105 to 150 kg m^{-3}, although modern high-compression balers can achieve a density of up to 230 kg m^{-3} [10, 11]. To put the densities of

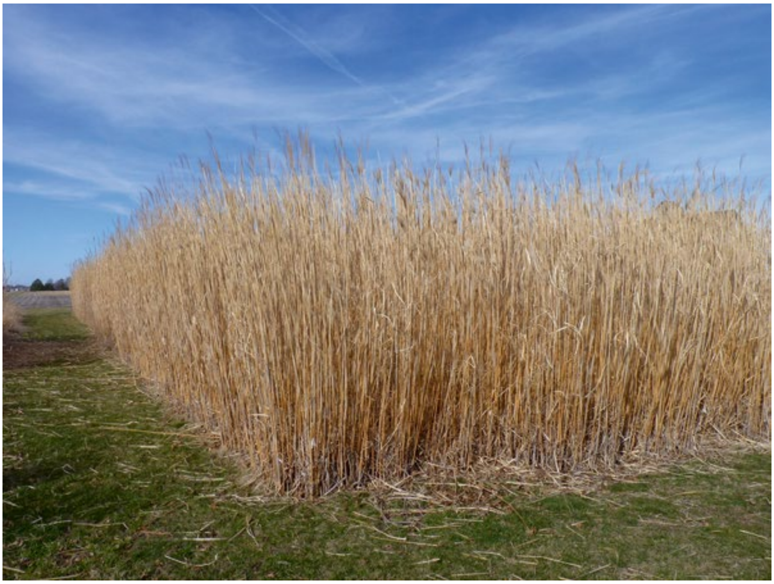

Fig. 6.1 A stand of *Miscanthus giganteus* ready for harvest. At harvest time in winter, no leaves are present, and nutrients have been recycled to the root system

crops in perspective, Table 6.2 shows the mass density in kg m^{-3}, the specific energy in MJ kg^{-1}, and the energy density in MJ m^{-3} of corn, *Miscanthus giganteus*, sugar cane bagasse and switchgrass, and, as a comparison, coal.

An advantage of second-generation biomass feedstock over, for instance, sugar cane is that it can be stored for longer periods, albeit at the cost of a gradual quantitative and qualitative loss of biomass. However, at some point along the provision chain, the form of the material needs to be changed because the conversion plant cannot process baled material directly. Therefore, comminution (size reduction) must take place to allow for optimal pretreatment and conversion. The determination of the optimal location for comminution along the provision chain now becomes important. For smaller biorefineries, bales could be directly delivered using truck transport, and comminution could take place at the biorefinery itself. For larger biorefineries, the transportation distances are much larger, which makes road transport expensive and rail and water transport more attractive. In rail and water transport, there is potential for creating a large number of regional depots, sometimes termed centralized storage and preprocessing centers (CSPs), which are connected to the biorefinery using rail or water transport. However, bales do not possess sufficient density to optimize long-distance transportation in railcars. To optimize rail transport, compression of the material is needed before transportation either in bale form or in post-comminution (powdered) form. Railcars could be developed with an integral loading/compression mechanism that ensures an optimal material density for transportation. One of the drawbacks of early stage comminution is that the powdered material needs to be stored in containers. Bales, on the other hand, can employ

Table 6.2 Energy content of biomass feedstock in various forms

Feedstock	Form		Mass density (kg/m^3)		Specific energy (MJ/m^3)	Energy density (MJ/m^3)		Reference
			Min	Max		Min	Max	
Coal	Lignite			600	28.47		17,082	a
	Anthracite			850	35.30		30,005	a
Corn				720	15.28		11,002	b
Miscanthus giganteus	Loose		70	100	17.10	1,197	1,710	c
	Milli	1 mm		265	17.10		4,532	d
		2 mm		235	17.10		4,019	d
	Compacted	Baled	130	150	17.10	2,223	2,565	c
		Pelletized		620	17.10		10,602	e
Sugarcane baggase	Loose		50	75	18.10	905	1,358	c
Switch grass	Loose			108	19.06		2,058	c
	Milli	1 mm		260	19.06		4,954	d
		2 mm		220	19.06		4,193	d
	Compacted	Baled	105	133	19.06	2,001	2,534	c
		Pelletized		620	19.06		11,814	e

(a) Coal. (n.d.). In Wikipedia. Retrieved June 27, 2013 from http://en.wikipedia.org/wiki/Coal
(b) Maize. (n.d.). In Wikipedia. Retrieved June 27, 2013 from http://en.wikipedia.org/wiki/Maize
(c) Scurlock, J. (n.d.). Biomass Feedstock Characteristics. Retrieved June 27, 20913 from https://bioenergy.ornl.gov/papers/misc/biochar_factsheet.html
(d) Miao Z., Grift T.E., Hansen A.C., Ting K.C. Energy requirement for comminution of biomass in relation to particle physical properties. Industrial Crops and Products 2011;33: 504–513
(e) Miao Z., Grift T.E., Hansen A.C., Ting K.C. Energy requirement for lignocellulosic feedstock densifications in relation to particle physical properties, pre-heating and binding agents. Energy & Fuels 2013;27: 588–595

inexpensive twine since the longer biomass strands gives some rudimentary rigidity. A commonly applied option is to compress powdered material into self-contained pellets or briquettes. If biomass pellets could be produced with a bulk density of coal in a pile, the existing coal infrastructure could be expanded, enabling transportation of the massive amounts of biomass needed to reach the stated goal of a 30 % replacement of the current US oil consumption by 2030. In addition, having materials with the same density makes blending easier since the gravitational segregation effect is eliminated, although segregation caused by varying particle size remains.

The feasibility of potential preprocessing methods, including methods for comminution, depends on the feedstock origin, physical properties of the material, and the biorefinery input requirements. In contrast to green energy crops, dry herbaceous energy crops and agricultural residues are characterized by low moisture content and a low bulk density at the senescence stage. The harvest window of prairie grasses is about 2–3 months long, during which the moisture content falls below 20 %. Windrowing and field drying after cutting and conditioning can reduce the "baling moisture" content to approximately 15 %. Since the moisture content is inversely proportional to leaf loss, timely harvest, baling, and preprocessing are of the essence, especially for round bales [12]. At harvest time, green energy crops have a high moisture content of up to 50 %, which makes preprocessing and storage more challenging than in the case of dry biomass. For instance, the majority of the existing milling machines, such as knife and hammer mills are incapable of fine size reduction of wet lignocellulosic feedstock. The same problem is present in sugar cane mills, where roller mills produce bagasse particles that are usually larger than 25.4 mm. Because of the high moisture content of green energy crops, typical road transportation vehicles reach their weight limit before their volume limit, which is suboptimal. Green energy crops also exhibit high fiber content, resulting in higher preprocessing energy consumption compared to dry biomass crops. Preprocessing of green energy crops such as short-rotation coppiced willow and poplar can utilize chippers and shredders for size reduction. Energy cane and energy sorghum are currently using sugar cane technology to extract juice with high sugar content. Forest-based biomass, including lumber wood logs, branches, and foliage, possess high moisture content, high fiber content, and a high bulk density. Similar to green energy crops, forest biomass preprocessing is challenging. Forest-based biomass often grows on hill slopes and marginal lands with limited accessibility; therefore, harvest and transportation of forest biomass is more difficult than that of dedicated energy crops and agricultural residues, which grow in farm fields and plantations. River transportation has been used to transport wood logs in some areas. Transpiration methods have been proposed to dry forest-based biomass, but the method is dependent upon many uncertain factors, such as weather and soil moisture. Since forest biomass does not have a distinct harvest window, to circumvent storage, just-in-time (JIT) harvest and transportation approaches are suitable.

6.3 Feedstock Preprocessing

The three main preprocessing methods consist of baling, size reduction, and pelletization. Common biomass forms include rectangular and round bales, pellets, and briquettes generated by extrusion, chopped forms such as generated by a self-propelled forage harvester (SPFH), and milled forms after size reduction by various types of milling machines.

6.3.1 Baling and/or Bundling

Bales comprise the most common biomass feedstock form used for on-road transportation. Baling is one of the elementary steps of one- or two-pass biomass harvest and collection systems as discussed in Chap. 5. For prairie grasses, the two-pass harvest system includes cutting, conditioning, infield windrowing, and baling. For agricultural residues such as corn stover, the two-pass harvest system includes one

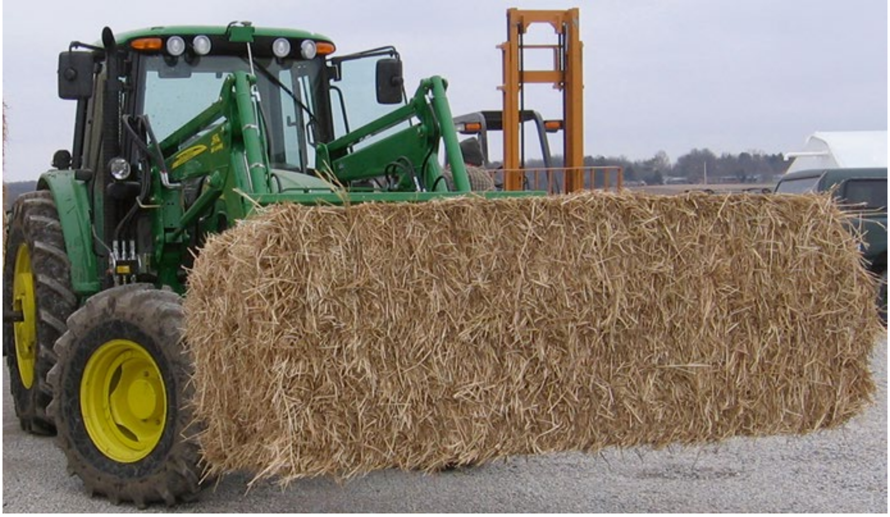

Fig. 6.2 *Miscanthus giganteus* in a square bale form

pass for grain collection and another where cutting, chopping, and/or baling takes place. Single-pass whole-crop harvest systems are sometimes used for prairie energy crops and agricultural residues. For short-rotation woody coppice, the single-pass harvest system comprises cutting and baling. The efficiency of two wood harvesters, a single-pass Biobaler and a two-pass Fecon mulcher cutting head combined with a Claas baling system, were compared in earlier research [13].

Round and square baling equipment is common in North America. Baling machinery designed for energy crops can produce square bales with a dimension of 122 × 122 × 244 cm, weighing as much has 454 kg (Fig. 6.2). The bale density of herbaceous grasses and agricultural residues typically ranges from 150 to 200 kg DM m^{-3}, although balers designed for bioenergy feedstock can reach 230 kg m^{-3}. Specialized stationary round baling machines, such as the BaleTech3, can reach values ranging from 360 to 400 kg m^{-3}. Round baling equipment has been widely adopted for forage hay, agricultural residues, forest residues, and short-rotation woody coppice. Figure 6.3 shows a set of round switchgrass bales on a flatbed trailer. The capacity of large round balers varies from 227 to 1,134 kg, and bale sizes range from 1.2 m diameter × 1.2 m wide to 1.8 m diameter × 2.4 m wide. The bulk density of round bales ranges from 100 to 170 kg m^{-3} for herbaceous biomass and from 321 to 373 kg m^{-3} for short-rotation wood coppice or forest residues [13]. Round bales are more difficult to load and stack compared to square bales, and consequently have higher storage and transportation costs, especially for long-distance transportation and large-scale stacked storage [6]. Although theoretically the porosity among round bales stacked in a triangular configuration as present in Fig. 6.3 amounts to 9.3 %, in practice, the top bales settle into the void spaces, reducing the porosity. The possibility and merit of filling a standard-sized ISO

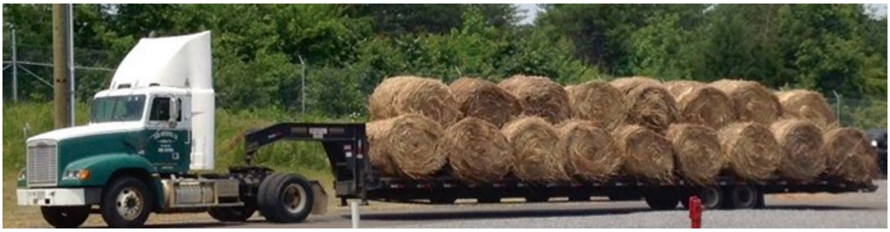

Fig. 6.3 Tractor trailer carrying round switchgrass bales

container with 32 round bales was investigated, and the conclusion was that the packing time required to load the container presented the limiting factor [14]. Round bales have higher biomass losses than rectangular bales during storage, but they are preferred for completely open storage since they shed rain water more effectively.

A developing trend for harvesting and collecting dedicated energy crops and agriculture residues is the single-pass harvest-chopping-baling combine. This machine has the advantage of reducing soil contamination and biomass loss by circumventing infield windrowing, at the cost of requiring lower biomass moisture content at harvest time. The single-pass system can also be applied to stover harvesting, where a combine separates grain and agricultural residue simultaneously [15]. The development of the single-pass machine started over a decade ago, when the Haimer company produced the Biotruck 2000, which combined a SPFH with a drying system (elegantly using the engine's waste heat) and a pelletization unit. The material density of the pellets ranged from 850 to 1,000 kg m^{-3}, and the bulk density of the pellets, from 300 to 500 kg m^{-3} [16].

6.3.2 Size Reduction

As shown in Table 6.1, comminution of biomass is imperative, since the conversion processes cannot directly process crops as they grow in the field. Size reduction can take place during harvesting, such as in the SPFH, which contains a chopping mechanism and a chute that pneumatically conveys the low-density chopped material into a wagon. Balers typically also have a cutting mechanism, but the size of the material strands is kept sufficiently long to allow baling using either string material in the case of square bales or netting or other forms of wrapping in the case of round bales. Further size reduction can take place at local depots or CSPs using wood chippers, such as those employed for tree harvesting, hammer mills, knife mills, and tub grinders that are often used to comminute bales for animal feed. Disk and attrition mills produce biomass particles of more uniform shape and finer size at a cost of higher energy consumption compared to hammer and knife mills [17–20]. The vibratory ball mill was found to be more effective than the rotary ball or rod mill in reducing cellulose crystallinity of spruce and aspen chips, generating fine particles and improving their digestibility [21, 22]. Polynomial relationships between bulk density and particle size of switchgrass, corn stover, wheat, and barley straw grindings were found [22] as

$$\rho_b = ax^3 + bx^2 + cx + d \tag{6.1}$$

Here, ρ_b is the dry bulk density in kg m^{-3}, x is the geometric mean diameter of particles in mm, and a, b, c, and d are regression coefficients. The relationship between the dry bulk density and particle size of wheat straw and switchgrass (for particles larger than 8 mm) can be described by a power law equation [10] in the form

$$\rho_b = ax^{-b} \tag{6.2}$$

where ρ_b is the dry bulk density in kg m^{-3}, x is the nominal particle size in mm, and a and b are regression coefficients. The functions as shown are specific to crop species, initial biomass properties, milling machine type, and machine parameters.

Size reduction can also increase the bulk density of the biomass and, therefore, can be regarded as a form of densification. The bulk density of chopped biomass (greater than 25.4 mm) before finer size reduction is typically less than 80–100 kg m^{-3}. For Miscanthus, it has been shown that the bulk density of the ground biomass through a screen with an aperture size of 4 mm can reach values of 150 kg m^{-3}, which are well in the range of typical field-produced bales [20]. By grinding biomass through a 1-mm screen and therefore performing further size reduction, a density of 250 kg m^{-3}, equal to that of bales produced by high-pressure balers, can be reached [20]. Although size reduction is an operation that requires ample energy, it could also be used as an alternative to chemical pretreatment [23, 24].

6.3.2.1 Energy Requirement of Size Reduction

Since size reduction is a key operation within the biomass provision chain, it is imperative to assess the energy consumption of the machinery. This can be achieved by monitoring the net input power that the machine requires for comminution and integrating this power over time. In general, the energy requirement of comminution is a function of the cutting mechanism (knife, hammer, ball), motor speed, feed rate, material feeding mechanism, strength of the milled material, and degree of size reduction [20, 25–31]. The specific energy consumption of biomass comminution is given as

$$E = f\left(r,\ sc,\ c,\ x,\ mc,\ p\right) \tag{6.3}$$

Here, E is the specific energy consumption, r is motor speed of the milling machine, sc is the milling or chopping machine scale, c is the material composition, fiber angle and/or structure, x is the ratio of initial and output particle sizes, mc is the moisture content in % w/w, and p is the applied axial pressure [10, 20, 22, 32]. Independent of the machine scale, a power (or exponential) law was found appropriate to describe the relationship between energy consumption and resulting particle sizes.

Experiments have shown that the energy consumption of size reduction is high: For instance, to grind air-dried (8 % moisture) Miscanthus through a screen with an aperture size of 1 mm, 5 PIHV was required. Willow ground through the same screen required up to 12 PIHV. By extrapolating these results, a particle size representing 100 PIHV, at which the energy required for comminution is equal to the inherent heating value of the material, was 80 μm for Miscanthus and 50 μm for switchgrass.

The biomass moisture content also has a significant impact on the energy requirement for comminution: The energy requirement for comminution of Miscanthus and switchgrass with a moisture content of 15 % was roughly 1.5 times higher than that of the same crops with a moisture content of 8 % (air-dried) [21].

6.3.3 Biomass Compression

Table 6.2 shows the energy densities of *Miscanthus giganteus*, switch grass, sugar cane bagasse, corn, and coal. When Miscanthus is baled, its energy density ranges from 2,223 to 2,565 MJ m^{-3}. Corn in bulk form on the other hand has an energy density of 11,002 MJ m^{-3}, over four times higher. Anthracite coal in comparison has an energy density of 30,005 MJ m^{-3}, which is 11.7 times higher than that of baled Miscanthus. It is clear that mechanical compression of biomass is essential to optimize the transportation efficiency, since at low material bulk densities the transportation medium reaches its volume limit far before its weight limit [33].

On-road flatbed and box trailer vehicles in the United States are limited to carrying materials with a density of 231 kg m^{-3}; thus, the achievable infield density of bales is well matched to on-road vehicles. This is, however, not the case for long-distance rail transport. Typical "gondola-type" railcars for coal are designed such that they reach their weight and volume limits simultaneously [34]. If biomass could be transformed into particulates with a bulk density equal to that of coal (850 kg m^{-3}), the existing coal transportation infrastructure could be expanded upon to accommodate the huge feedstock transportation task in the future.

Mechanical compression of biomass is a poorly understood process since the biomass' mechanical properties in general and rheological properties in particular are rather elusive. The compression process can be divided into three distinct phases: (1) removal of air, (2) compression of biomass under material reorganization, and (3) compression of material in a settled matrix. In the first process, little pressure is needed, since merely the material porosity is reduced. In the second process, during which particulates move and fill the pores, exponential or power law functions seem to adequately describe the relationship between the applied force and biomass volume [4]. The third phase, where the biomass essentially behaves like a solid and Hooke's law may apply, is only reached at extremely high pressures. During a high-pressure experiment using Miscanthus as a test medium, this behavior was observed at applied pressures of more than 350 MPa [35].

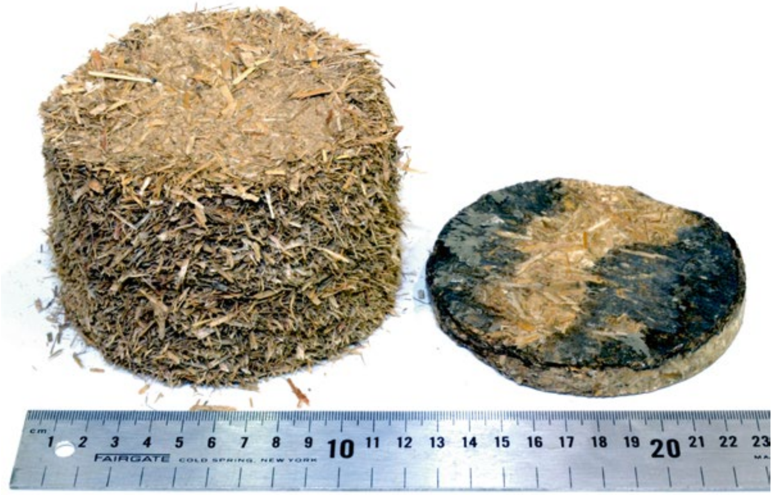

Fig. 6.4 *Left*: sample of Miscanthus ground to 12.7-mm particle size at a density of 350 kg m^{-3}. *Right*: sample after being exposed to a pressure of over 750 MPa at a density of approximately 1,470 kg m^{-3}

6.3.3.1 Energy Requirement for Biomass Compression

The energy requirement for compression of biomass can be calculated by monitoring the force applied onto the biomass by a piston and integrating this force across the distance through which the piston travels during the compression. As in the case of comminution machines, for extruders, the net input power the machine required for compression can be monitored and integrated over time. In both cases, the energy requirement pertains to the net energy needed for compression, without taking into account energy required to run ancillary equipment. To determine the pressure needed to compress biomass to a desired value, a sample of biomass was compressed with a universal testing machine, capable of producing a force of 13 MN [35]. Figure 6.4 shows the sample before the test, pre-compressed to a density of 350 kg m^{-3}, and after the test at a density of approximately 1,470 kg m^{-3}. Figure 6.5 shows the energy requirement for compression of the same pre-compressed sample in PIHV. It is clear that the energy requirement is proportional to the density and that a power law seems adequate to capture this relationship. Note that compression to 1,000 kg m^{-3} required only 0.035 PIHV and that compression up to a density of 1,321 kg m^{-3} required only 0.1 PIHV: Even compression to a very high density of 1,767 kg m^{-3} required merely 0.315 PIHV. The conclusion of this research was that energy consumption for compression is not an inhibiting factor. However, the machinery required to produce particulates of this density level at a large throughput would most likely be expensive.

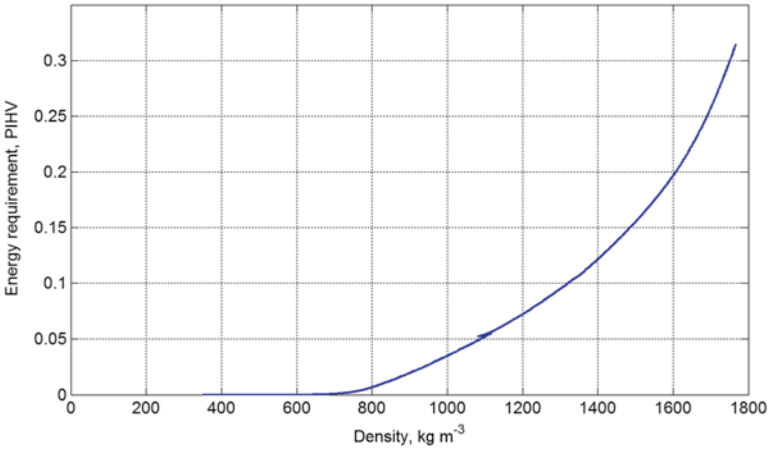

Fig. 6.5 Energy requirement in PIHV for compression of the sample shown in Fig. 6.4, versus the “in-mold” density

Finally, there is a common misconception that compressing biomass may diminish its inherent energy-producing potential. No evidence has been shown in the literature that this is the case. Further research is needed to determine the effect of compression on the biomass conversion efficiency.

6.3.4 Pelletization

Pellets, briquettes, and cubes made from biomass have the advantage of yielding a flowable material form, which is suitable for long-distance rail transportation [4, 11]. To produce pellets, biomass feedstock needs to be ground to a particle size of approximately 2–8 mm and compressed while potentially applying increased temperatures and binding agents. The energy requirement for pelletization is a function of the particle size, the required pellet material density, and the required pellet quality which includes durability, a function of the pellet hardness [4, 36]. Typical biomass pellets have a diameter ranging from 12 to 15 mm [32].

One of the drawbacks of pelletized material in bulk form is that it exhibits porosity due to air pockets among the pellets. Various mathematical models predict the porosity of randomly packed cylindrical particles in a bulk material as a function of the pellets’ aspect ratio, which, for typical biomass pellets, ranges from 1.5 to 2.5. In this range, the so-called Z-Y model predicts a porosity of approximately 0.32 [37]. To reduce the porosity, secondary compression of bulk pellets may be feasible; however, this method may compromise the integrity of the pellets.

A second limiting factor is long-term post-compression rebound, which is defined as the increase in volume of the pellet after the pressure applied during pelletization has been removed. This effect can amount to over 30 %. Taking both post-compression rebound and porosity into account, to achieve a desired bulk density of pelletized material, the "in-mold" density of the material must be over twice as high. In addition, when biomass material flows through channels at extreme pressure levels, the material can potentially self-combust [35]: The compressed sample shown on the right side of Fig. 6.4 exhibits areas where the biomass was charred due to excessive heat during compression. This heat caused localized pyrolysis in which volatile gases are produced. These gases subsequently ignited, which led to an explosion.

6.3.5 Storage

Lignocellulosic biomass is typically harvested in a short-time window of about 2–3 months. Since the aim of the conversion plant is to produce fuel year round, storage of biomass is needed. The issues of the location of the storage operation within the provision chain, the conditions of storage, and the infrastructure required are still being addressed in research. Due to the low energy density and monetary value of the material, uncovered outdoor stacking of bales may be most economical, but long-term uncovered storage will incur quantity losses and possibly the emergence of fungi and molds that are detrimental in the conversion process. Bales, either round or square, may be a viable option before comminution, since inexpensive twine is sufficient for containment. Wrapping bales in plastic for long-term storage may prevent biomass loss, while allowing a high bale density and stacking on unprepared grounds, but it requires low moisture content and is expensive. If storage is to take place after comminution, the biomass must be preprocessed into a self-contained compressed form such as pellets or briquettes, since storage of powdered low-density biomass would be very inefficient. This is the idea behind the Advanced Uniform Format as proposed by the Idaho National Laboratory [6].

6.4 Transportation

The success and sustainability of the biofuel industry depend largely upon an efficient feedstock provision system, in which transportation plays a key role [6]. While it will provide a huge economic opportunity for communities across the United States, harvest, preprocessing, storage, and transportation of massive amounts of biomass will be challenging [38]. Dependent upon the biomass densification level and transportation mode, transportation represents between 13 and 28 % of the feedstock provision costs, which limits the collection area. Taking into account the US Department of Transportation's legal load limit of 21.8 tons for on-road transportation, at least 150,000 road trips will be required per day by 2030 to transport three million tons of biomass feedstock from farms to biorefineries.

With a throughput rate of 15–20 ton h^{-1} attainable by tub grinder hammer mills, over 6,250 such machines would be required to comminute the three-million tons of biomass feedstock to an average particle size of 25.4 mm. For a medium-sized biofuel plant with a daily demand of 2,000 dry tons of feedstock, more than 100 trips would be required per day [11].

In a typical bioenergy feedstock production process, the crop is collected and cut using a harvester, conveyed into wagons that transport materials in fields, and transloaded into trucks that transport the material either directly to a conversion plant or to a CSP. To illustrate the logistics involved in the production of fuels from bioenergy feedstock, a conceptual biomass provision system that includes a CSP is shown in Fig. 6.6. The sequence of events as illustrated is as follows:

1. Farmers deliver the biomass in bale form to the CSP using trucks, since the distances from the field to the CSP are relatively short. The advantage of using balers is that they are readily available, farmers are familiar with their workings, can maintain them, and can capitalize on the advantage that the containment of the biomass can be accomplished using inexpensive strings or netting and relatively low-tech machinery. The density that is achievable using modern balers allows flatbed trucks to reach their volume and weight limits simultaneously.
2. At the CSP, bales are stored and possibly dried using waste heat from the engine that powers the comminution and pelletization operations. The road traffic from farms to the CSP is seasonal and intermittent, similar to that occurring during the harvest season of corn and soybean.
3. The task of the CSP is to preprocess the biomass feedstock through comminution. This operation runs continuously and is directly followed by a pelletization operation; in fact, ideally the two operations are combined in a single large machine, which allows containment of dust while preventing “dust explosions.” Before pelletizing, the biomass could be treated with bonding agents and potentially pretreatment agents. In addition, the CSP provides storage, loading, and blending facilities for the pelletized material.
4. An elegant method of conserving energy is to use the biomass itself as the energy source for the CSP. This would require direct combustion of the pelletized biomass and employing energy conversion such as through a Stirling engine. This is a constant-power machine, which runs on a temperature differential, where the “hot” end is created by burning an arbitrary fuel (in this case biomass pellets) and the “cold” end consists of a heat sink connected to the outside ambient temperature. This is an advantage in colder climates, because the temperature differential is naturally higher, compared to more temperate climates. The Stirling engine also produces “waste heat,” which can be used for biomass drying. After milling, the pelletized biomass is stored in large bins, similar to current storage of corn and soybean.
5. The loading of the gravity-flowable pelletized biomass can take place using classical handling equipment such as augers, chutes, and conveyor belts. In addition, the CSP can operate bins containing various biomass types and blend them

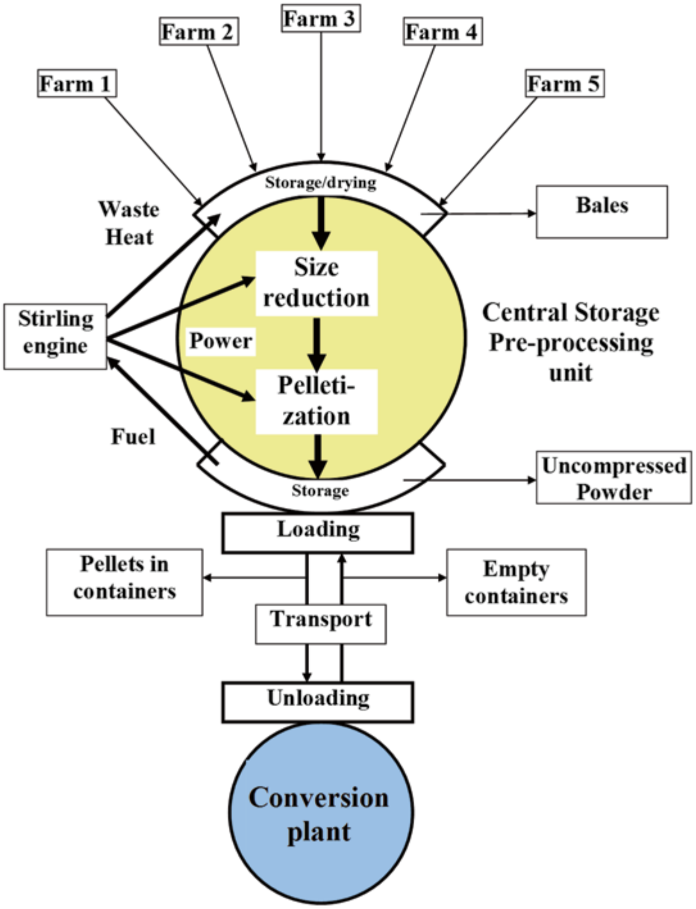

Fig. 6.6 Concept of a field-to-refinery feedstock provision system

according to the needs of the conversion plant. Secondary compression of the pelletized biomass may be an option to reduce the porosity and increase the bulk density.

6. The transportation between the CSP and the conversion plant takes place in railcar containers for bulk goods. The traffic flow between the CSP and the conversion plant is continuous, similar to current processing plants where a fixed number of railcars arrive daily, eliminating the need for long-term storage at the conversion plant. At the conversion plant, the pelletized biomass is dumped in a large collection bin, after which the pellets can be either mechanically crushed or dropped into a liquid for pretreatment.

6.4.1 Truck Transport

Green biomass such as sugar cane is perishable and needs to be processed ideally within a few hours after harvest. Therefore, in this case, short-distance truck transport is effective but not necessarily efficient. Since green biomass can have a moisture content of over 50 %, the weight limit is typically reached before the volume limit.

Flatbed trailers are often used for bale transport, and by taking into account volume and weight limits, the maximum density of the bales is 223.5 kg m^{-3} [35]. This value is achievable using modern baling technology.

Transloading is defined as the operation that moves goods from one form of transportation to another such as from a truck to a railcar or barge or vice versa. Each transloading operation can incur losses and damage, therefore the logistics system needs to be designed to minimize the number of transloading operations. Transloading of biomass in bale or containerized form can be achieved using traditional equipment such as cranes, forklifts, stackers, and bulldozers. Pelletized material can be conveyed using belts, augers, and chutes, while powdered material can be conveyed pneumatically.

Specialty trucks such as concrete carriers and dump trucks have an exempt status in terms of weight limit, but biomass is not likely to reach densities that warrant the use of such equipment.

6.4.2 Rail Transport

Short-distance transport of biomass using trucks is well suited to the achievable density of bales. However, the rail to truck fuel efficiency ratio of gondola-type railcars (such as those used for coal transport) ranges from 2.3 to 4 [39], making rail transport more efficient than truck transport. This is especially valid for long-distance transportation for which rail transport has lower operating (variable) costs than truck transport; this reduction offsets the higher capital (fixed) cost associated with rail transport. For straw and corn stover, in North America, the minimum economic rail shipping distance (MERSD), the point where rail transport becomes more economical than truck transport, is 170 km. The value for boreal forest harvest residue wood chips is 145 km due to its higher density [40].

6.4.3 Water Transport

The same issues associated with rail transport are present in water transport using barges and even ocean-going vessels. Any material in bulk form can be transported using railcars or ships, but only efficiently if the bulk density of the material is such that the volume and weight limits can be reached simultaneously. The main difference between ships and trains is that for a given loading volume, trains, supported by rail, can, in principle, accommodate densities much higher than the density of water, and ships cannot, since sufficient residual buoyancy must be maintained.

6.4.4 Pipeline Transport

Pipeline transport of biomass in a slurry form is an attractive idea, since the pipeline itself is stationary and the material is inherently contained. In the paper industry, slurries are used to convey pulp, but only for relatively short distances. High-concentration slurry disposal (HCSD) is a modern approach to remove fly ash from power plants over distances up to 10 km with a solids fraction of 70 %. For biomass to follow a similar strategy, the biomass density should ideally be similar to that of the carrying fluid (typically water), which is not the case.

The economics of pipeline biomass transport have been studied, leading to the conclusion that for flows over two million dry ton yr^{-1} and distances ranging from 100 to 500 km, pipeline transport is less expensive than truck transport [41]. However, technical limitations render the concept unfeasible since research has shown that the biomass will readily absorb the carrier fluid: woodchips absorb water from an initial water content of 45 % to over 60 % in a matter of hours. This reduces the lower heating value of the material to virtually nil. The same material in oil reached an oil content from initially zero to over 30 % after 120 h [42]. This leaves the possibility of adding biomass such as woodchips to an oil flow in existing pipelines, but the oil-pumping infrastructure, including pumps and valves, is dependent upon the fluidic behavior of oil, and adding biomass would require major engineering adaptations. The consensus found in the literature is that pipeline transport is not a feasible option for biomass transportation.

6.4.5 Biomass Transportation Logistics

Supply and biorefinery logistics represent critical barriers in energy generation from biomass [3, 6, 11, 43, 44]. Biomass supply logistics are dependent upon the conversion technology utilized, production capacity (i.e., feedstock demand), feedstock type, yield (i.e., feedstock supply) as well as pathways and technologies that make feedstock supply meet demand. In general, the components of biomass feedstock supply chain mainly include biomass harvest/collection, baling, loading, transport in the field and/or long-distance, transloading, storage, mechanical comminution and feedstock transformation (e.g., pelletization and torrefaction). At tactical and operational levels, feedstock transportation logistics are dictated by farm and biorefinery location, daily or hourly biomass quantities to be transported, handled and mechanically processed, numbers and time schedule of harvest machines, transportation vehicles, processing and handling equipment, labor requirements and personnel costs, route selection, as well contingency scenarios. In the sugar industry, various analysis tools for harvest, transportation and processing have been developed [45].

6.5 Future Directions

This section addresses some concepts that may hold promise in the future, but are currently under research.

6.5.1 Modeling

Systems analysis involving techniques of modeling, simulation and optimization can be used to study the complete feedstock provision chain, while circumventing experimentation. There are multiple levels to perform such analyses. Modeling can be used for strategic optimization, such as to determine the optimal locations to produce a bioenergy crop in relation to agronomic and environmental parameters, and social and economic driving forces, as well as to determine the optimal placement of CSPs and conversion plants related to land use policy and infrastructure availability. At a tactical level, models can be used to predict the utilization of the storage and transportation infrastructure over time. At an operational level, models can be used for real-time logistics, transportation fleet tracking, and to manage uncertainties such as adverse traffic and weather events. The main bottleneck is not the modeling effort itself, but rather the lack of pertinent data needed to drive the models, in addition to the potential unwarranted use of outputs of models that have not been properly validated [46].

6.5.2 Standardization

For a medium or large commercial biofuel plant, biomass forms and equipment performance could be standardized to streamline supply logistics and improve efficiency of biomass supply systems [11, 47]. For small-scale pilot biofuel plants, existing agricultural equipment and facilities for biomass feedstock preprocessing, storage, and transportation may be feasible. However, for medium or large commercial biofuel plants, standardized harvest, preprocessing, and supply equipment need to be developed. An example of this is the development of self-propelled bale loading/unloading equipment by the US Department of Energy's Biomass program [2].

The quality of feedstock is currently poorly defined, and a standard is needed here as well. This quality parameter should include not only feedstock composition and energy density, but also grindability, flowability, storability and, most importantly, convertibility potential.

In research, there is a need for reporting results in a consistent standardized manner. Apart from the fact that, to date, ample literature in the United States still uses the archaic English Unit system, there are other areas where inconsistencies arise. For instance, for size reduction, the specific energy consumption per unit of resulting particle area (MJ m^{-2} particle area) should be used for efficiency evaluation rather than the specific energy consumption per unit of mass (MJ kg^{-1}). For energy requirement, it is logical and intuitive to express energy usage of machinery in the PIHV, rather than Joule/tonne or worse, in BTU/lb. In economic studies, the use of purchase power parity is more sensible than using currencies such as US$ or Euro.

6.5.3 Interface Between Feedstock Provision and Conversion

Research to date has either focused on the biomass provision chain or bio-conversion aspects. The schism between the provision and conversion research is understandable, since they have traditionally been disconnected by pretreatment. There is an urgent need for a concerted effort to observe the bioenergy provision and conversion process in a holistic manner, rather than as individual entities.

6.5.4 Biomass Pretreatment During Storage

Storage of biomass is a liability, but it can also be an asset. The duration of storage can be long, and during this time, there is an opportunity to expose the biomass to chemicals for slow pretreatment. The most accessible form of biomass is directly after size reduction, but this form has a very low density requiring large volumes of storage. A superior option may be to treat the biomass with a pretreatment agent between the size reduction and pelletization operations. This concept of pretreatment during storage has had little attention in the literature.

6.5.5 Feedstock Preprocessing

Among the three main operations during biomass provision—harvesting, size reduction, and compression—size reduction is by far the most energy-intensive. For instance, size reduction of Miscanthus through a screen with an aperture size of 1 mm requires up to 5 PIHV, whereas woody biomass such as willow [20] required 12 PIHV. To reduce the energy requirement of size reduction, dedicated milling machines that employ knives with optimal cutting angles and serrations, potentially fitted with long-lasting ceramic coatings, operating at a cutting speed that minimizes energy use within an acceptable throughput window, are essential.

The energy use for compression is much lower than that of size reduction, but the machinery needs to be designed such that it can exert extremely high pressures onto the material, at a very high throughput rate, without excessive cost in machine investment. Explosions due to localized pyrolysis must be prevented.

Ideally, machines that combine the size reduction and compression (pelletization) operations could be developed that give the advantage of limiting dust generation. Within the machine, between the size reduction and pelletization actions, additives could be applied that aid in the bonding/durability of the pellets. The machine should be controlled such that machine operates at an optimal temperature for pelletization and additive efficacy.

6.5.6 Sensing Technology and Automation

Sensing technology is needed in various steps of the feedstock provision and conversion process. In comminution, sensors are needed to control feeding rates and cutting speeds, allowing the machines to operate most efficiently. At the gates of CSPs and conversion plants, real-time sensors are needed to measure, for instance, the moisture content of the biomass, which can be accomplished using classical indicators such as capacitance. However, to determine the “quality” of feedstock, sensors are needed for rapid assessment of conversion efficiency (RACE).

6.6 Summary

The main task of the feedstock provision system is to deliver biomass to a pretreatment and conversion system in sufficient quantities and in a form that allows these systems to be optimized while simultaneously optimizing its own processes.

Transportation is a key step in the provision system. Apart from transportation mode and logistics management, the provision system also includes aspects of preprocessing such as size reduction and compression that affect the transportation efficiency. Harvesting, which is energetically inexpensive, can take place using either adapted grass/forage cutting and baling equipment, or chopping machines such as the self-propelled forage harvester (SPFH).

Size reduction (comminution) is a key operation in the provision chain because pretreatment/conversion process cannot deal with uncut material directly. Apart from comminution being an energetically expensive operation, the optimal location of comminution in the provision chain is not clear. For smaller conversion plants that utilize short-distance truck transport, bales may be delivered to the conversion plant where comminution takes place. In this case, storage could take place either in field or at the conversion plant. The density of bales produced with modern equipment is such that trucks (typically flatbed types) are reaching their volume and weight limits simultaneously, allowing optimal transportation efficiency. For larger conversion plants, however, the transportation distances are much larger, and rail transport becomes more efficient and economical. In this case, centralized storage and preprocessing centers (CSPs) are needed that store bales and transform the feedstock into a stable, storable, blendable, and gravity-flowable form, such that the feedstock becomes a marketable commodity. The bulk density of the particulates in the flowable form must allow railcars to reach their volume and weight limits simultaneously. For instance, gondola-type coal railcars can accommodate the density of coal in a pile, which is 850 kg m^{-3}, rendering the production of biomass with a similar bulk density attractive. However, to produce such a bulk density, the "in-mold" density of the particulates comprising the bulk material needs to be over twice as high as the bulk density, to compensate for post-compression rebound and porosity. Overall, compression of biomass is energetically inexpensive, but the machinery that can deliver massive amounts of highly compressed biomass is arguably expensive. The same bulk form must also allow the conversion plant to efficiently pretreat and convert the feedstock into liquid fuels.

Water transport using barges is another option for long-distance biomass transportation, although the dispersion of waterways limits its application domain and the bulk density of the material being transported must be significantly lower than that of water. Pipeline transport, where biomass in particulate form is suspended in a carrier fluid, has been shown unfeasible for transportation of biomass.

In the near future, several technologies must be developed/optimized to make bioenergy a realistic alternative to fossil fuels. To integrate ongoing and future developments, the generation of comprehensive models on strategic, tactical, and operational levels must be pursued. These models must include the latest research data and technologies, and be properly validated before any conclusions can be gleaned from them.

References

1. Perlack R, Wright L, Turhollow A, Graham R, Stokes B, Erbach D (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. U.S. Department of Energy Oak Ridge National Laboratory, Oak Ridge, TN. p: 1–78
2. U.S. Department of Energy Biomass Program (2012) Feedstock supply and logistics: biomass as a commodity. DOE/EE-0766. Available at: https://www1.eere.energy.gov/bioenergy/pdfs/feedstocks_four_pager.pdf (verified on Dec. 13, 2013)
3. Humbird D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, Schoen P, Lukas J, Olthof B, Worley M, Sexton D, Dudgeon D (2011) Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis of corn stover. U.S. Department of Energy National Renewable Energy Laboratory, Golden, CO. p: 1–114
4. Miao Z, Grift T, Hansen A, Ting K (2013) Energy requirement for lignocellulosic feedstock densifications in relation to particle physical properties, pre-heating and binding agents. Energy Fuel 27:588–595
5. U.S. Department of Energy (2011) U.S. Billion-ton update: biomass supply for a bioenergy and bioproducts industry. U.S. Department of Energy Oak Ridge National Laboratory, Oak Ridge, TN. p: 1–227
6. Hess J, Kenney K, Ovard L, Searcy E, Wright C (2009) Commodity-scale production of an infrastructure-compatible bulk solid from herbaceous lignocellulosic biomass. Idaho National Laboratory, Idaho Falls, ID

7. Mosier N, Wyman C, Dale B, Elande R, Lee Y, Holtzapple M, Ladisch M (2005) Features of promising technologies for pre-treatment of lignocellulosic biomass. Bioresour Technol 96:673–686
8. Alizadeh H, Teymouri F, Gilbert T, Dale B (2005) Pre-treatment of switchgrass by Ammonia Fiber Explosion. Appl Biochem Biotechnol 124(1–3):1133–1141
9. Chundawat S, Ventakesh B, Dale B (2007) Effect of particle size based separation of milled corn stover on AFEX pre-treatment and enzymatic digestibility. Biotechnol Bioeng 96(2):219–231
10. Lam P, Sokhansanj S, Bi X, Lim C, Naimi L, Hoque M, Mani S, Womac A, Ye X, Narayan S (2008) Bulk density of wet and dry wheat straw and switchgrass particles. Appl Eng Agric 24:351–358
11. Miao Z, Shastri Y, Grift T, Hansen A, Ting K (2012) Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configuration and modeling. Biofuels Bioprod Bioref 6:351–362
12. Smith J, Grisso R, VonBargen K, Anderson B (1988) Management tips for round bale hay harvesting, moving, and storage. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=2306&context=extensionhist. Accessed 28 June 2013
13. Do Canto J, Klepac J, Rummer R, Savoie P, Seixas F (2011) Evaluation of two round baling systems for harvesting understory biomass. Biomass Bioenergy 35:2163–2170
14. Cundiff J, Grisso R (2008) Containerized handling to minimize hauling cost of herbaceous biomass. Biomass Bioenergy 2008:308–313
15. Shinners K, Boettcher G, Hoffman D, Munk J, Muck R, Weimer P (2009) Single-pass harvest of corn grain and stover: performance of three harvester configurations. Trans ASABE 52(1):51–60
16. El Bassam N, Huisman W (2001) Harvesting and storage of Miscanthus. In: Walsh M, Jones M (eds) Miscanthus for energy and fibre. James & James, London, pp 86–108
17. Bruglieri M, Liberti L (2008) Optimal running and planning of a biomass-based energy production process. Energy Policy 36(7):2430–2438
18. Aggarwal A, Singh H, Kumar P, Singh M (2008) Optimizing power consumption for CNC turned parts using response surface methodology and Taguchi's technique: a comparative analysis. J Mater Proc Technol 200:373–384
19. Zhu J, Wang G, Pan X, Gleisner R (2009) Specific surface to evaluate the efficiencies of milling and pre-treatment of wood for enzymatic saccharification. Chem Eng Sci 64:474–485
20. Miao Z, Grift T, Hansen A, Ting K (2011) Energy requirement for comminution of biomass in relation to particle physical properties. Ind Crop Prod 33:504–513
21. Kumar P, Barrett D, Delwiche M, Stroeve P (2009) Methods of pre-treatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. Ind Eng Chem Res 48:3713–3729
22. Mani S, Tabil L, Sokhansanj S (2004) Grinding performance and physical properties of wheat and barley straws, corn stover and switch grass. Biomass Bioenergy 27:339–352
23. Alvo P, Belkacemi K (1997) Enzymatic saccharification of milled Timothy (Phleum Pratense L.) and alfalfa (Medicago Sativa L.). Bioresour Technol 61:185–198
24. Badger P, Fransham P (2006) Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs-A preliminary assessment. Biomass Bioenergy 30:321–325
25. Akunov F (1995) Generalized grinding law. Chem Pet Eng 31(3–4):208–211
26. Cadoche L, López G (1989) Assessment of size reduction as a preliminary step in the production of ethanol from lignocellulosic wastes. Biol Wastes 30:153–157
27. Jannasch R, Quan Y, Samson R (2001) Final report: a process and energy analysis of pelletizing switch grass. Resource Efficient Agricultural Production (REAP), Ste. Anne de Bellevue, QC
28. Morrell S (2008) A method for predicting the specific energy requirement of comminution circuits and assessing their energy utilisation efficiency. Miner Eng 21:224–233
29. Bitra V, Womac A, Chevanan N, Miu P, Igathinathane C, Sokhansanj S, Smith D (2009) Direct mechanical energy measures of hammermill comminution of switchgrass, wheat straw, and corn stover and analysis of their particle size distributions. Powder Technol 193:32–45

30. Igathinathane C, Womac A, Sokhansanj S, Narayan S (2008) Knife grid size reduction to pre-process packed beds of high- and low-moisture switchgrass. Bioresour Technol 99(7): 2254–2264
31. Igathinathane C, Womac A, Sokhansanj S, Narayan S (2009) Size reduction of high- and low-moisture corn stalks by linear knife grid system. Biomass Bioenergy 33(4):547–557
32. Mani S, Tabilb L, Sokhansanj S (2006) Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenergy 30(7):648–654
33. Tumuluru T, Wright C, Hess J, Kenney K (2011) A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. Biofuels Bioprod Bioref 5(6):683–707
34. Freightcar America Inc. (2012) http://www.johnstownamerica.com/Coke-Coal-Railcars.htm. Accessed 14 Aug 2012
35. Miao Z, Phillips J, Grift T, Mathanker S (2013) Energy and pressure requirement for compression of Miscanthus giganteus to an extreme density. Biosyst Eng 114:21–25
36. Kaliyan N, Morey R (2009) Densification characteristics of corn stover and switchgrass. Trans ASABE 52(3):907–920
37. Zou R, Yu A (1996) Evaluation of the packing characteristics of mono-sized non-spherical particles. Powder Technol 88:71–79
38. Richard T (2010) Challenges in scaling up biofuel infrastructure. Science 329(5993):793–796
39. International ICF (2009) Comparative evaluation of rail and truck fuel efficiency on competitive corridors. U.S. Department of Transportation, Federal Railroad Administration, Washington, DC
40. Mahmudi H, Flynn P (2006) Rail vs truck transport of biomass. Appl Biochem Biotechnol 129–132:88–103
41. Searcy E, Flynn P, Ghafoori E, Kumar A (2007) The relative cost of biomass energy. Appl Biochem Biotechnol 136–140(1–12):639–652
42. Kumar A, Flynn P (2006) Uptake of fluids by boreal wood chips: implications for bioenergy. Fuel Process Technol 87:605–608
43. Rentizelas A, Tatsiopoulos I, Tolis A (2009) An optimization model for multi-biomass tri-generation energy supply. Biomass Bioenergy 33:223–233
44. Gunnarsson C, Vågström L, Hansson P (2008) Logistics for forage harvest to biogas production—timeliness, capacities and costs in a Swedish case study. Biomass Bioenergy 32(12):1263–1273
45. Le Gal P, Lyne P, Meyer E, Soler L (2008) Impact of sugarcane supply scheduling on mill sugar production: a South African case study. Agric Syst 96(1–3):64–74
46. Miao Z, Grift T, Hansen A, Ting K (2013) An overview of lignocellulosic biomass feedstock harvest, processing and supply for biofuel production. Biofuels 4(1):5–8
47. Lyne P (2010) The latest in transport management and technologies. SAIAE News Lett 3–5
48. Sustainability Program, Office of Research and Development, U.S. Environmental Protection Agency (2007) Biomass conversion: emerging technologies, feedstock, and products. EPA/600/R-07/144